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MR Fluids for Possible Use in Smart Devices

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ABSTRACT: - Smart fluids also known as Magnetorheological fluids (MR Fluids), behave like a Newtonian fluid without the presence of a magnetic field but in few seconds change its rheological properties when an external magnetic field appears. In this research, Smart Fluids were synthesized, carbonyl iron particles with different grades were used, oil and water emulsions were employed as a continuous phase and silicon dioxide as surfactant. The influence of the properties of soft magnetic particles over Smart fluids was investigated by using a Transmission Electron Microscope (TEM) to see the morphology and X-Ray Diffraction to confirm the quality in phases. Magnetic properties in particles and fluids were determined by Vibrating Sample Magnetometer (VSM). The Smart Fluid Rheological properties were studied by a rotational Rheometer (MCR500, Anton Paar) with the commercial magnetorheological device MRD and a coaxial parallel plate system with 20 mm (PP 20/MR) diameter. The aim of this project was to study all the factors directly with the performance of Smart Fluids. Our results probe that the particles are well involved in the surfactant which can help to decrease the sedimentation rate, and also to increase the yield strength. With FMR1M a high yield stress (37.5 kPa) was achieved in comparison with others previously reported.

KEYWORDS: - Smart fluids, Magnetorheological behaviour, stability, yield stress, Smart devices

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I. INTRODUCTION

Nowadays the tend to build smart devices is requiring the researchers focusing in studies to create or developed Smart Materials, which can be controlled by an external field, such as electric, magnetic or temperature gradient. Magnetorheological (MR) fluids belongs to Smart Materials type whose rheological characteristic change within a few seconds on the application of an external magnetic field. Due to these properties, MR fluids have the ability to provide simple, rapid-response interfaces between electronic controls and mechanical systems. The main components in these fluids are ferromagnetic particles, a carrier fluid as a continuous phase and some additives. The devices based on MRF have potential applications in numerous fields such as automobiles (brakes, clutches and shock absorbers), civil constructions (seismic dampers), exercise & fitness equipment, [1,2,3,4,5], thermal fluid in aeronautic devices [6] and lately they could be used as a “blood” for robots (Prosthetic hand) [7,8,9].

A smart fluid can replace the conventional mechanism as electrical, hydraulic or pneumatic motors. In a MR fluid its shear behavior is typically described as that of a classical Newtonian fluid, which is a material that does not flow unless the applied stress exceeds the yield stress. For MRFs, the yield stress is a function of the applied field strength. If a movement wants to be achieve in a Robot, the Smart fluid is used as an active medium in order to generate a variable magnetic force, which is going to be controlled by the current through the coil installed [9]. The yield shear stress is the main figure of merit of a Smart fluid although that specific property is directly related with the nanoparticles physical properties. Most of the ferromagnetic particles contain iron which is one of the heaviest element in periodic table (55.84 g/mol), therefore the gravity effect is going to provoke precipitation of those particles.

An important necessity is to develop smart suspensions with fast response rate and wide stability. Actually most of the magnetorheological fluids show a constant setting throughout their lifetime, due to the high density of magnetic particles or by the formation of “hard cake”, which is a strong aggregation caused by remnant magnetization between the particles, hard to re-disperse even without magnetic field application [10]. Several additives in order to reduce particles surface tension have been used (oleic acid, silicon oil, sodium carboxymethyl cellulose, etc.) [11]. Other researchers have try to avoid the formation of “hard cake” by coating the particles using some polymers as polyvinyl-butyral (PVB) getting positive results [12]. Prekas et. al., proved that the particles sedimentation can be influenced by temperature and surfactant concentration [13]. All these factors make the wear of particles crucial in affecting the properties of smart fluids.

The aim of this project is to study the effects over stability and performance by variating the surfactant, type of magnetic particles according to the continuous phase. Our results probe that the particles are well involved in the surfactant which can help to decrease the sedimentation rate. With FMR1M a high yield stress (37.5 kPa) was achieved in comparison with the ones previously reported.

II. EXPERIMENTAL

PREPARATION OF SMART FLUIDS

In this research six Smart fluids were obtained (Table I), three different grades of carbonyl iron ($Fe(CO)_5$ from ISP Technologies) were used, with a density of 4.4 g/cm^3, with different sizes to study the size effect over Smart fluid stability (R1470 (9 µm), S1281 (5 µm) and R2430 (5 µm)). The fraction of ferromagnetic particles used was 35 % by volume [10]. For the several projected application requirements carrier fluids include mineral oil or water, also contain some additives to prevent sedimentation and aggregation of particles to improve their lubrication properties and stability.

Firstly, 35 g of carbonyl iron powder were dispersed in mineral oil (density 0.838 g/cm^3), containing 5 % v/v of sodium carboxymethyl cellulose and silicon dioxide as a surfactant for Smart fluids water and oil based respectively. Such suspensions were agitated for 6 hrs. with a mechanical stirrer at 300 rpm.

Table I. Smart fluids obtained

	MR1A	MR1M	MR2A	FMR2M	MR3A	FMR3M
particle	R1470		S1281		R2430	
Carrier fluid	Water	Mineral oil	Water	Mineral oil	Water	Mineral oil

III. MAGNETIC PARTICLES CHARACTERIZATION

In order to verify the magnetic particles quality, they were characterized by scanning electron microscopy (SEM), model JEOL ASM 6360A and Energy-dispersive X-Ray spectroscopy (EDS), their magnetic properties by vibrating sample magnetometer (VSM). Also when the particles belong to the Smart fluids were characterized.

1. Smart fluids Properties

3.1 Stability

The sedimentation problem is a big issue for Smart fluids because is directly related to with the good performance. The calculations of stability were obtained by using the Stoke's Law, which allows to determine the sedimentation velocity of certain fluid by relating the viscosity (η), density (ρ), gravity (g), and considering spherical particles (r) with the next formula (1) [9]:

$$v = \frac{2r^2 g\rho}{9\eta} \qquad (1)$$

One liter container was filled up with each Smart fluid which is clearly marked and then the separation between the two phases was recorded.

1.2 Rheological properties

For getting insight into rheological behavior of the Smart fluids obtained, a rotational rheometer (MCR500, Anton Paar) with the commercial magnetorheological device MRD and a coaxial parallel plate system with a diameter of 20 mm (PP 20/MR) was used. The distance between the plates was adjusted to h=0.3 mm in order to optimize the sensitivity, three different magnetic fields with the flux density of B=0,0.2,0.6 T were used. The analysis were taken at room temperature (25° C), using a volume of the fluid sample of 170 µl. Viscoelastic properties of Smart fluids were measured using the "magneto sweep" method, described by Wollny et al. [11].

1.3 Thermal stability

The thermal behavior of each material was obtained by using a TA Instruments HI RES model TGA 2950, with temperature range of 100-800 ºC, air feed of 10 cm^3/min.

IV. RESULTS AND DISCUSSION

1. Magnetic particles characterization

Magnetic particles X-Ray Diffraction (XRD) confirm the presence of iron cubic α-Fe phase (figure 1a). By scanning electron microscopy (SEM) can be observed that the three types of particles have spherical shape with a wide size distribution and also the surfactant can be seen covering the particle surface when is forming the Smart fluid (figure 1b).

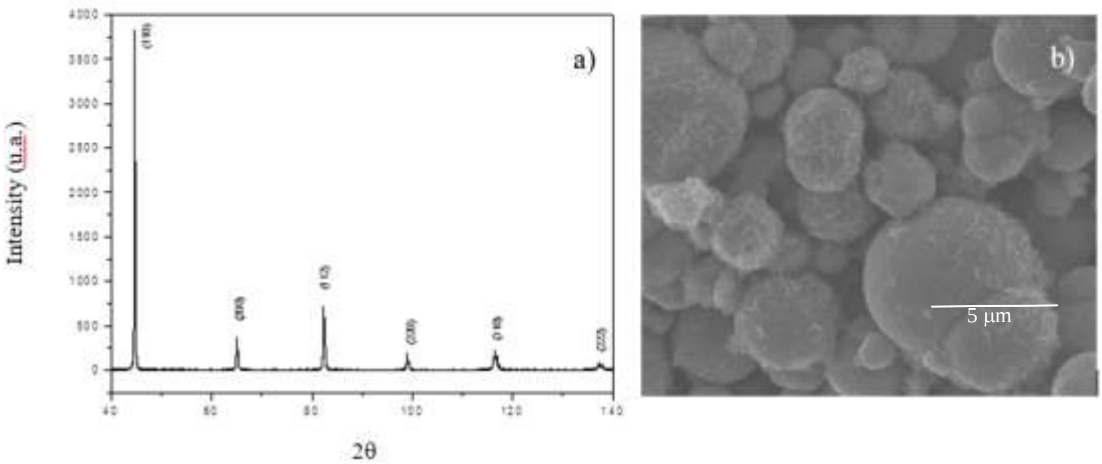

Fig. 1. Micrograph for a) S1281 and b) S1281particles forming Smart Fluid FMR2M.

Table II. EDS analysis for carbonyl iron used

Type	C % w	Fe % w
R-1470	1.06	98.94
S-1281	1.68	98.32
R-2430	0.5	99.50

From the EDS analysis (table II) can be seen the purity of the magnetic particles used to obtain the Smart fluids, which is going to be directly related to rheological behaviour on the smart fluid. As it can be seen in table 1 the particles type R-2430 have less Carbon content.

2. Particles Magnetic properties

The analysis took place using a VSM LDJ, model 96000, which is calibrated with a niquel weight of 0.409 g, magnetization=54.9 emu/g @ 10,000 Oe. In Table III, the hysteresis loop data are given in the range of 180-191 emu/g. The coercivity force is the amount of magnetic field that needs to be applied so the material can return to magnetic flux zero. For the R1470 particles this coercivity force is the highest, which can have a negative effect over fluid stability due to the remain forces that can act to form agglomerates and accelerate the sedimentation rate.

Table III. Magnetic particle properties

Particle	Magnetization Saturation (emu/g)	Retentivity (emu/g)	Coercivity field (Oe)
R1470	191	0.68	18
S1281	180	0.24	7
R2430	190	0.28	8

The S1281 particles type show the lowest magnetization saturation which can be related to the highest content in carbon observed by EDS (table 2). According to C. Fang et al., in order to have magnetic particles as a good candidate to form a magnetorheological fluids or Smart fluid, they need to have low retentivity and coercivity, high saturation magnetization and small loop hysteresis [12]. In agreement with results for a better performance in a Smart fluid, the type of R2430 particles are preferred.

3. Smart fluids Properties

3.1 Stability

For sedimentation rate calculations for water and oil density and viscosity data were needed. Sedimentation velocities for all fluids are exhibit in table IV. All the samples were placed in test tubes and observed for 72 hrs. In base of the results we can confirm that surfactant showed very good enhancement of stability against gravity, mainly with FMR2M and FMR3M.

Table IV. Sedimentation velocity for Smart fluids obtained.

Smart fluid	Particle density (g/cm^3)	Displacement (cm)	Sedimentation velocity (cm/h)
FMR1A	7.80	0.0004	74.8238
FMR1M	7.80	0.0004	0.4695
FMR2A	7.54	0.00025	28.1105
FMR2M	7.54	0.00025	0.1765
FMR3A	7.80	0.00027	34.0916
FMR3M	7.80	0.00027	0.2139

As it can be seen from results the particles in water based fluids would fall faster than in the mineral oil based fluids. In Stokes formula the sedimentation velocity is directly related to particle and Carrier's fluid density, therefore and in base of results obtained, a higher time stability for the mineral oil-based (FMR2M**)** is predicted. Althought similar results were obtained for FMR1M and FMR3M the sedimentation velocity increased in doble for FMR1M which contains the biggest size in particle (9 μm). For the suggested applications sedimentation should be as low as posible otherwise it is going to affect the yield strength produce by the Smart fluid.

1.4 Themal stability

Graphs in figure 3 show a significant weight loss in smart fluids after a temperature of 100 °C for water based fluid and around 250°C for mineral oil based fluids. This weight loss is directly related to the evaporation of the carrier fluid taking into account the boiling point. Nearly 350°C water based fluids starts to gain weight due to oxidation of carbonyl iron particles. On the other hand, the oxidation for magnetic particles in mineral oil based fluids start around 450°C and the gain in weight is less than in water based fluids. This thermal stability is going to be related to the fluid's operating temperature range. Althoug the Smart fluid water based themal stability is not high, still for biomedical applications it can be applied.

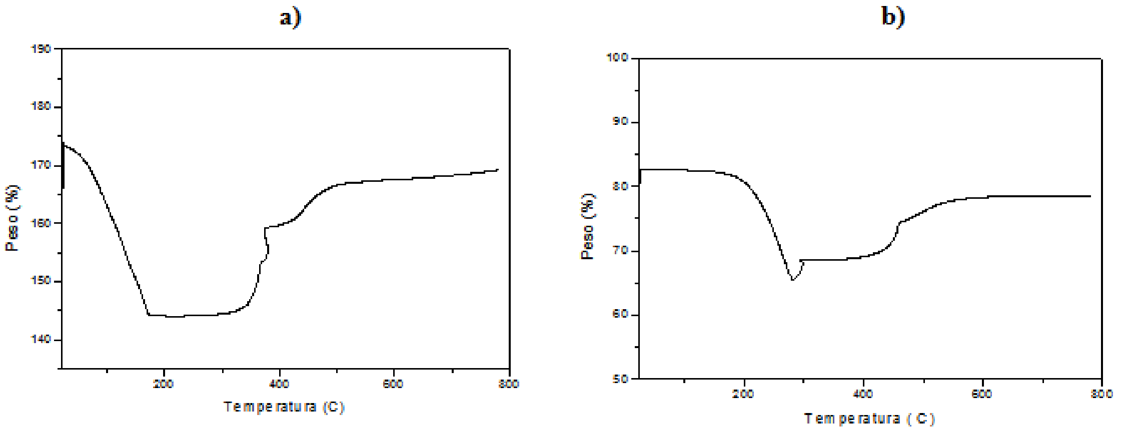

Fig. 2. Thermograph for a) FMR1A and b) FMR1M.

1.5 Magnetic properties

The hysteresis loop obtained for all the magnetic particles and Smart fluids can be considered as a hard magnetic material because of the hysteresis loop shape. As it was expected the coupling between the magnetic particles in a carrier fluid vanishing magnetic field strength. Therefore magnetization saturation went down as it can be seen in fig. 3.

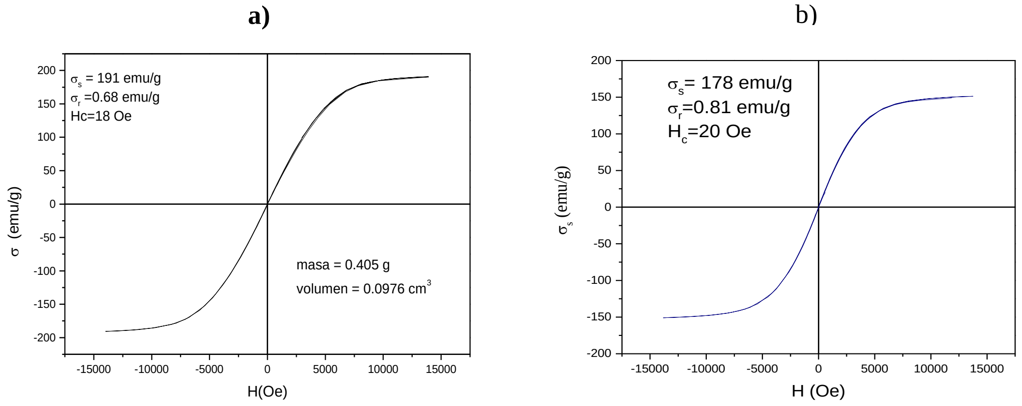

Fig. 3. a) Magnetic properties of Particles R1470, and b) magnetic properties of Smart fluid FMR1M

3.6 Rheological Properties

As it can be seen in figure 4 a), all Smart fluids show a yield point at 10 Pa when there is no magnetic field applied (B=0 T), which is the minimum stress needed so the fluid starts flow, after that the shear rate increase in a no lineal form meaning viscosity decrease while shear rate increase. This behaviour is directly related with a pseudoplastic fluid.

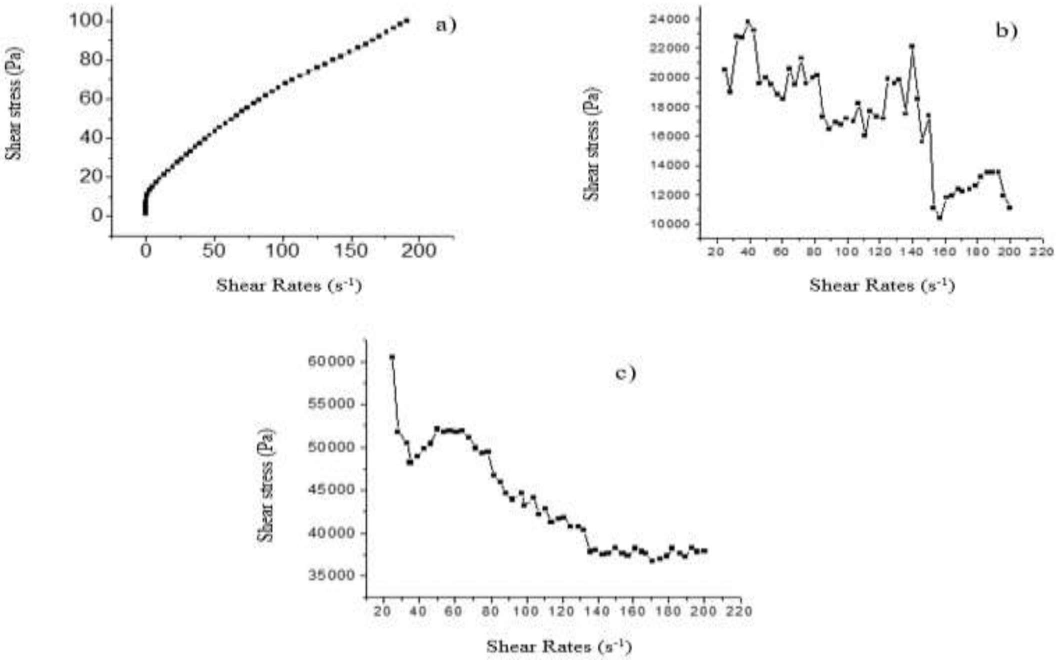

Fig. 4. Shear stress versus shear rate for FMR1M: a) B= 0 T, b) B=0.2 T and c) B=0.6T.

When the magnetic field is applied the interaction between magnetic particles becomes significant because of the formation of large chains and the strength of those will determine the viscous behaviour of Smart fluids. Yield stress values of fluids ranging from 10 to 60 kPa at a magnetic field of B= 0, 0.2 and 0.6 T. Due to the rheological behaviour of Smart fluid or magnetorheological fluid vary with the shear stress (Pa) and shear rate (s^{-1}), there are classified as thixotropic fluids which means that the shear stress decrease with increasing the shear rate (figure 4 b) and c)). Although the highest Shear stress (60kPa) reported was obtained for FMR1M based with R1470 grade of carbonyl iron, when a magnetic field of 0.2 T was applied, it can be observed that the chain structure will break down and recovery rate probably because of the adsorbed surfactant layer, which can cause slow down the movement of particles in the oil medium (figure b). In figure 4c), can be observed that while shear stress and shear rate decrease also, for other hand the FMR1M fluid at a B=0.6 T got an equilibrium value around 37.4 kPa. The high apparent yield strength of fluids was attributed to the high saturation magnetization of these particles (191 emu/g).

V. CONCLUSIONS

The study of six Smart fluids were carried out by verifying the effect over rheological properties related with the type of magnetic particles, carrier fluid and surfactant used. It was possible obtain a Smart fluid capable of change its viscosity in seconds when a magnetic field is applied and with an acceptable stability. Based on characterizations results the Smart fluid samples obtained mineral oil based, are good option for several applications as a brake, damper, knee prosthetic, etc., also the size of magnetic particle should be chosen carefully because that is going to help increasing the stability fluid and therefore the yield strength. The yield strength obtained was high (37.5 kPa) compare with the already reported for others magnetorheological fluids, which is going to open the possibility of applications.

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